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Report No. 10

**Quarterly Progress Report on  
INVESTIGATION OF MICROWAVE DUPLEXER  
SWITCHING MECHANISMS**

**268 229**

Contract No. DA-36-039-SC-78313

File No. 18716-PM-59-91 (4967)

**U. S. ARMY  
SIGNAL CORPS ENGINEERING LABORATORY  
Fort Monmouth, New Jersey**

Department of the Army Task  
No. 3A99-13-001-05



**ELECTRICAL ENGINEERING RESEARCH LABORATORY  
ENGINEERING EXPERIMENT STATION  
UNIVERSITY OF ILLINOIS  
URBANA, ILLINOIS**

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| <p>AD <u>Accession No.</u> <u>Unclassified</u></p> <p>Electrical Engineering Research Laboratory<br/>University of Illinois, Urbana, Illinois 1. Gaseous<br/>INVESTIGATION OF MICROWAVE DUPLEXER SWITCH-<br/>ING MECHANISMS by M. Roux, 1 July 1961 to<br/>30 September 1961, 35 pgs., 9 illus., 2. Contract<br/>(Contract DA-36-039-SC-78313) SC Project No. DA-36-039-<br/>323 B, DA Project No. 3-99-15-104, Quarterly<br/>Progress Report No. 10, Unclassified.</p> <p><u>Abstract</u></p> <p>During this quarter, the investigations intended to determine the character of the waves propagating in the plasma formed in a tube by a high power RF pulse has been continued using a mixture of gases exhibiting the charge exchange effect. The experimental results obtained to date seem</p> | <p>AD <u>Accession No.</u> <u>Unclassified</u></p> <p>Electrical Engineering Research Laboratory<br/>University of Illinois, Urbana, Illinois 1. Gaseous<br/>INVESTIGATION OF MICROWAVE DUPLEXER SWITCH-<br/>ING MECHANISMS by M. Roux, 1 July 1961 to<br/>30 September 1961, 35 pgs., 9 illus., 2. Contract<br/>(Contract DA-36-039-SC-78313) SC Project No. DA-36-039-<br/>323 B, DA Project No. 3-99-15-104, Quarterly<br/>Progress Report No. 10, Unclassified.</p> <p><u>Abstract</u></p> <p>During this quarter, the investigations intended to determine the character of the waves propagating in the plasma formed in a tube by a high power RF pulse has been continued using a mixture of gases exhibiting the charge exchange effect. The</p> |
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QUARTERLY PROGRESS REPORT NO. 10  
ON  
INVESTIGATION OF MICROWAVE DUPLEXER SWITCHING MECHANISMS

15 October 1961

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Contract DA-36-039-SC-78313  
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Prepared By:

M. Roux

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Engineering Experiment Station  
University of Illinois  
Urbana, Illinois

## PURPOSE

The over-all problem has been divided into two parts; studies of basic mechanism associated with microwave duplexer switch operation, and applications of these studies to duplexer components and circuits.

The study of basic mechanisms was commenced in this laboratory under Contracts DA-36-039-SC-52670 and DA-36-039-SC-73150. Under these contracts, work was conducted on the following aspects of the basic switching operation:

- 1) The multiplication of electrons in a gas under the action of a high level electromagnetic field, and the time element involved in the multiplication process.
- 2) The leakage of RF energy through the switch during the breakdown process referred to in (1). The spike leakage power was resolved as a function of time, and electron motions during breakdown were analyzed.
- 3) Electric charge removal processes that influence deionization and the recovery time of the switch.
- 4) Basic studies leading to an approach to the entire switching problem using a semiconductor in place of a gaseous medium.

Under the present contract, work is continuing on the last two aspects of basic mechanisms. These include investigation of the properties of gas discharge plasmas containing electron attaching gases, and investigation of basic properties of semiconductors in microwave fields as a first step towards possible applications.

## ABSTRACT

During this quarter, the investigations intended to determine the character of the waves propagating in the plasma, formed in a tube by a high power RF pulse has been continued using a mixture of gases exhibiting the charge exchange effect. The experimental results obtained to date seem to indicate the presence of sound waves in the neutral gas as well as pseudo sound waves in the gas of the ions. The plasma, created by the high power RF pulse, extends in the tube far away from the region where this pulse is applied, as a result of the energy leaking from this region. Theoretical considerations and experimental evidence indicate that this energy progresses along the tube by means of a surface mode of propagation. The validity of the detection of the discontinuities by means of the light intensity has been verified by a microwave method. The presence of the discontinuities is evidenced by an enhanced attenuation in the transmitted microwave signal. Problems associated with the limitation in the range of detection by microwaves are discussed.

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## FACTUAL DATA

### TASK A: INVESTIGATION OF MICROWAVE DUPLEXER SWITCHING MECHANISMS

#### 1. Introduction

We have reported previously\* that the breakdown of a gas by a pulsed, high power level, RF wave gives rise to perturbations in the gas which has the general properties of longitudinal or sound waves. When the gas is contained in a cylindrical glass tube, a small length of which is plunged in the waveguide carrying the high power level pulsed RF wave, the perturbations produced as a result of gas breakdown are observed to propagate in two different modes. One mode of propagation is along the axis of the tube while the other propagates radially. Two apparently distinct waves are observed to propagate along the tube.

We recall here that the fraction of the pulsed RF power, "leaking" out of the waveguide immediately after the gas broke down, is able to spread ionization in the gas contained in the section of the tube which is outside the waveguiding system. Thus, past the high level microwave pulse of  $1 \mu s$  duration, an afterglowing plasma is available for the delayed observation of the perturbations produced during breakdown and/or during the application of the  $1 \mu s$  duration high power level RF pulse. The method developed earlier in this laboratory,\*\* which enabled us to study low energy shock waves in gases, is then used to investigate the sound like perturbation produced as a result of gas breakdown by the high level RF pulses. It was feared that this leakage might interfere with the first mode of propagation and account for the existence of the second mode; it has been therefore decided to investigate its general behavior along the tube.

The question arises as to whether the perturbations thus produced are sound waves which propagate in the neutral gas or whether these are ionic sound or pseudo sound waves which propagate in the ion gas of the background afterglowing plasma. An attempt to identify these waves was made during the past quarter and is described below. The method consists of studying the variation of the velocity of propagation of the produced perturbation as a function of

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\* Quarterly Reports 8 and 9.

\*\* Quarterly Report 2

time when the nature of the ions is changed. In order to vary the nature of the ions in the plasma, a well defined gas mixture is used, in which, through the process of charge exchange, the nature of the background ions varies as a function of time. These experiments are described in this report. However, since the velocity of the ion waves is a function of both the ion mass  $M_1$  (to the  $-1/2$  power) and, for unequal charge temperatures ( $T_e \neq T_1$ ), also of the electron temperature  $T_e$  (to the  $+1/2$  power), a direct measurement of the electron temperature simultaneous to the measurement of the change in propagation velocity of the waves is necessary. The exact electron temperature being unknown at the present time, no definite conclusions have been reached as yet.

Thus far the presence and the propagation of the discontinuities have been exclusively based on the detection of a slight change in intensity these discontinuities produced in the visible light output of the plasma afterglow. In order to confirm the validity of this method, we have started experiments to detect these perturbations by means of microwave techniques. These techniques have been described in earlier reports. They consist in the detection of an attenuation increase produced by the perturbations in the transmission of an X-band microwave signal carried in a waveguide, which is traversed by the tube. Some phenomena limiting the range of detection are also discussed.

## 2. RF Power Leakage

### 2.1 Surface Mode of Propagation

It has been mentioned in the introduction that the high power RF pulse from the magnetron, when applied to the extremity of the tube introduced in the waveguide, not only produces there the rapid breakdown of the gas but also ionizes the gas over a long section of the tube outside the waveguide; the plasma thus obtained exhibits the characteristic afterglow, in which we have detected the discontinuities

Which mechanism is at the origin of this external ionization? In view of the usually high gas pressure and the small diameter of the vessel, an ionization by photons or fast electrons is unlikely to exist over such long distances. A heat flow from the breakdown region is ruled out owing to the large time constant involved in this process and to the large wall surface of the tube as compared to the RF heated volume of the gas. According to a theoretical and experimental study made in this laboratory by C. C. Leiby and P. D. Goldan, it has been

verified that a mode of propagation for an electromagnetic wave exists on the surface of a dielectric rod, when this rod satisfies certain conditions. The most important one is that the dielectric constant of the rod be less than -1. Such a situation may be found in an ionized gas as soon as the plasma frequency  $\omega_p$  is substantially greater than the RF signal frequency  $\omega$ , since its dielectric constant, in the case of an ideally unbounded and collisionless discharge, is given by

$$\epsilon = 1 - \frac{\omega_p^2}{\omega^2}; (\omega_p^2 \geq 2\omega^2) \quad (1)$$

With the presence of boundaries and collisions, additional terms require the ratio  $\omega_p^2/\omega^2$  to be slightly larger. We refer to this mode or waves as "surface mode" or "surface waves." Thus the propagation of a surface wave is possible along a plasma column of relatively high density (for an RF signal at 3000 mc and a ratio  $\omega_p^2/\omega^2 \simeq 5$ , the electron number density should reach  $10^{13} \text{ cm}^{-3}$ ). It should be immediately pointed out that, in the absence of a plasma, no such propagation mode exists along the glass tube alone (because of its small positive dielectric constant). Since however the ionization of the gas is experimentally observed, another physical phenomenon must be taken into account in order to explain how the breakdown by means of a surface mode of propagation can be started. This phenomenon is the diffusion of the electrons out of the ionized part of the gas.

From their theoretical study of the surface mode, Leiby and Goldan found that the longitudinal electrical field intensity varies radially across the plasma column and has a maximum on the plasma surface; on both sides of this maximum, the intensity decreases in first approximation exponentially. In the longitudinal direction, this field decreases also exponentially beyond the assumed sharp boundary of the plasma. A weak field is therefore present in the plasma volume and a stronger one close to the surface.\* Now, we believe that the following sequence of events occurs during the duration ( $1 \mu\text{s}$ ) of the high power RF pulse of the magnetron: in an extremely short time ( $< 10^{-8} \text{ sec}$ ), the gas in the section of the tube located inside the waveguide breaks down and

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\* It should be understood that this field is a result of the RF energy leaking outside the waveguide, for which the surface wave is a suitable mode of propagation. This field is therefore excited by, and at the same frequency as, the RF magnetron pulse.

builds up a relatively high density plasma. Due to their high thermal energy, many electrons escape this ionized volume and find themselves in the spacially decaying RF field extending beyond the plasma boundary, from which they get enough additional energy to ionize the gas atoms surrounding them. During this process, the electron density increases and brings the dielectric constant below -1, hence permitting the RF surface waves to extend up to this new plasma boundary outside the waveguide, and further heat the newly created plasma. The same process repeats itself in the next time elements, shifting the plasma boundary further and further down the tube, until a distance is reached where the surface waves have been sufficiently attenuated to prevent the diffusing electrons to be energized up to a high enough level to produce and sustain the discharge.

Since the plasma and the surface waves are mutually dependent on each other, it is expected that the velocity with which the plasma boundary progresses along the tube will be of the same order of magnitude as the thermal velocity of the electrons in the discharge, since this is the slowest phenomenon involved in this ionization process. It is also expected, in view of the radial field distribution of the surface mode, to find at the termination of the magnetron pulse a higher electron density close to the wall than on the axis of the tube. This density and/or energy gradient between the wall and the axis is believed to be at the origin of the cylindrical sound waves observed in all of our experiments.

One of the reasons for looking at the surface waves along the plasma, is to check if the metallic surfaces close to the tube, or more generally, any discontinuity in the propagation impedance of the wave, produced a standing wave pattern on the plasma. In case a too high variation of the electric field is detected, it would be necessary to determine to what extent these variations influence the propagation of the plane sound waves or are perhaps responsible for their formation.

## 2.2 Experimental Results

The investigation on the RF power leaking outside the waveguide was intended to give us the following information: a) Do we detect any RF energy along the tube at some distance from the waveguide? b) Does this energy show an important standing wave pattern? c) Is there any significant time delay between the

magnetron pulse and the detection of the RF energy leakage as well as the light intensity.

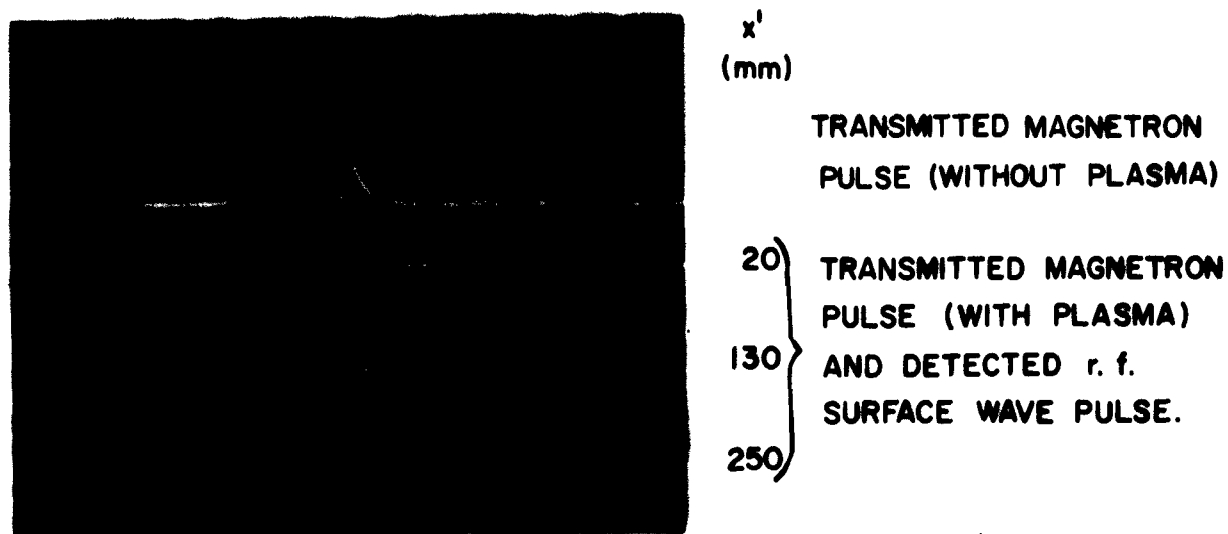
### 2.2.1 Detection of RF Energy along the Tube

The first question was rapidly answered by means of an RF electrical probe (actually a 442B Hewlett-Packard probe) with a 15 mm long antenna, placed perpendicularly to the tube at 4 mm of the wall (in the surface mode of propagation, the field outside the plasma has a component perpendicular to the tube axis). The probe is connected to a crystal detector through a 10 db attenuation pad (to prevent the saturation of the crystal) and the detected signal is then displayed on an oscilloscope alternatively with the detected signal from the transmitted RF magnetron pulse. By moving the probe parallel to itself along the tube it is verified that an RF energy is present along the whole length of the plasma column. Figure 1 is a multiple exposure picture showing the transmitted magnetron pulse and the RF field picked-up by the probe at different distances from the waveguide. The conditions of the experiment\* were: Neon 17.5 mm Hg. magnetron power  $\approx 25$  kw peak, pulse duration =  $1 \mu s$ , pulse repetition 250 cps, tube penetration in the waveguide  $p = 30$  mm, length of the plasma column  $x' = 260$  mm. (Actually, at 260 mm from the waveguide, the tube is connected to a metallic bellow; by an unfortunate choice of the experimental conditions, the plasma just reached the bellow and stopped there, so that the last few millimeters of the discharge could not be observed), sweep speed 0.5  $\mu s/cm$ , ordinate: arbitrary units, different for both signals.

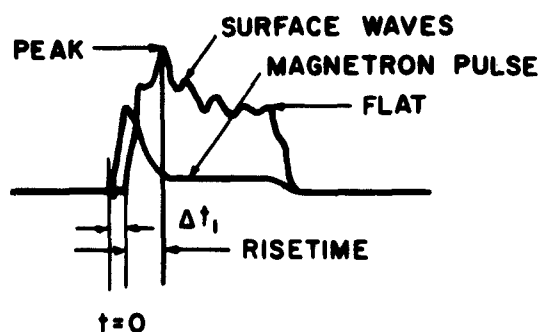
The upper trace in Figure 1 represents the transmitted magnetron pulse in the absence of the plasma and serves as reference for the time  $t = 0$ . The three lower traces display the same magnetron pulse, strongly attenuated by the plasma inside the waveguide, and the surface wave detected at a distance of 20, 130 and 250 mm from the waveguide. The sketch defines the time delay  $\Delta t_1$  between the beginning of the magnetron pulse and the starting point of the surface wave pulse and the "risetime" of the surface wave pulse between its starting point and its maximum. It also defines what we called the "peak" amplitude of the surface wave (the first sharp maximum observed at small distance  $x'$ ) and the flat part of the pulse (just before the end of the pulse). Three results can be obtained from this picture: with increasing distance  $x'$ , the

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\* For the definition of  $x'$  and  $p$ , see Quarterly Report No. 8, Figure 2.



(a)



(b)

Figure 1. a) Transmitted magnetron pulse (in the S-band waveguide) and detected RF surface waves (along the tube) as a function of time with distance  $x'$  between probe and waveguide as parameter. Upper trace, without plasma; three lower traces, with plasma. Neon 17.5 mm Hg, magnetron power=25 kw peak,  $p = 30$  mm,  $0.5 \mu s/cm$ ; b) Explanatory sketch for part (a) and for the definition of  $\Delta t_1$ , risetime, peak and flat.

amplitude of the surface wave decreases, the time delay  $\Delta t_1$  remains almost constant (with a higher gain, the lowest trace still fits with this observation), and the risetime of the surface wave considerably increases. The interpretation of these results is given in the discussion. Similar results have been obtained for a Helium plasma at 0.9 mm Hg, with the only difference that the risetime is half as long.

### 2.2.2 Possible Existence of RF Standing Waves along the Tube

As far as a possible standing wave pattern of the surface wave is concerned, measurements of the RF field amplitude at two different points of the pulse, peak and flat, have been made with the same probe in the same conditions as a function of the distance along the tube. Before recording the data however, we have checked that the presence of the metallic probe close to the plasma did not introduce by itself reflections of the surface waves and produce therefore a standing wave which would interfere with the measurements. For this purpose, we used a second probe located at some small but fixed distance from the waveguide and watched the variation of its output while the first probe was moved along the tube. A fluctuation of about ten percent was effectively observed in the signal detected by the second probe. This self perturbation has to be taken into account for the interpretation of the results.

Curves I and II in Figure 3 plot in arbitrary units respectively the peak and flat amplitude of the surface waves as a function of the distance along the tube. The amplitude of the peak, as defined in the sketch of Figure 1 and on page 5, is seen to decrease continuously and to progressively disappear. The next peak (curve I') is subject to the similar variation but at a greater distance. In general, the maximum amplitude of the pulse slowly decreases with distance. The amplitude of the flat has in the whole a slight tendency to increase. As far as standing wave is concerned, a small, roughly periodic ( $\sim 40$  mm) variation of the amplitudes is observed, which seems to be enhanced at the proximity of the bellow ( $x' = 260$  mm); these fluctuations are out of phase for the peaks and the flat. No large standing wave pattern is however detected. The measurements in the Helium plasma confirm these results.

### 2.2.3 Progression of the RF Energy and of the Light along the Tube

The detection of the light intensity along the tube during the breakdown of the gas was made, as usual, by means of a bunch of 4 quartz fibers and a

photomultiplier. Care has been taken not to saturate the latter. In order to compare the changes in the light and surface wave intensity, the light pipes and the RF probe were directed at the same point of the tube axis and moved together.

Figure 2 is a multiple exposure of the surface wave and light intensity detected at 20, 130, and 250 mm from the waveguide. The conditions of the experiment were the same as for Figure 1. The sketch defines the two time delays " $\Delta t_2$ " and " $\Delta t_3$ " respectively as the time intervals between the starting point of the surface wave and that of the light, and between the maximum of the surface wave and the starting point of the light. It also defines what we called the light "peak" (maximum intensity) and "flat" (light intensity at the end of the RF pulse). From Figure 2, the following results are obtained: with increasing distance  $x'$ , the peak light intensity remains constant,\* whereas the flat light intensity slowly increases,  $\Delta t_2$  increases from 0.17 to 0.79  $\mu$ s, and  $\Delta t_3$  remains almost constant.

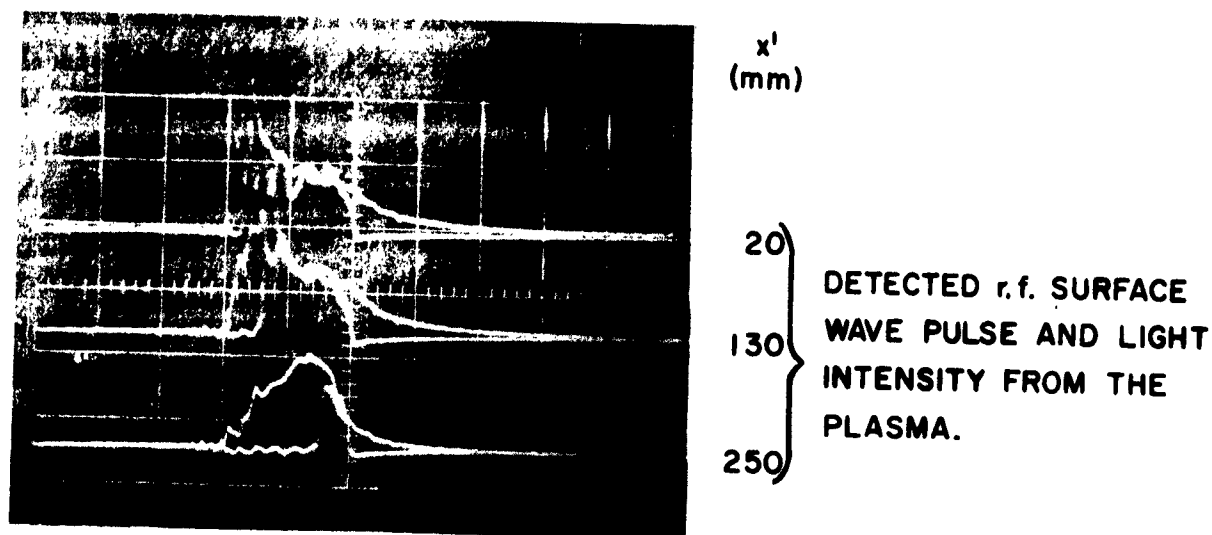
Curves III and IV in Figure 3 plot in arbitrary units the variations of the peak and flat light intensity as a function of the distance  $x'$  along the tube. From this figure, it is seen that the light intensity remains almost constant over the length of the plasma, with the exception that, beyond  $x' = 200$  mm, the peak and flat falls down to a lower intensity; since their percentile change is different, this fall cannot be attributed only to the increasing cross section of the tube beyond 200 mm. The lower intensity between 10 and 15 mm is a result of the multi-layer mylar isolation present there, which produces an attenuation in the transmission of the light. The irregular fluctuations on top of the curves can hardly be identified with standing waves. In the Helium plasma, however, the fluctuations on the light flat are periodic, more pronounced and out of phase with the surface wave flat; the other observations are similar.

### 2.3 Discussion

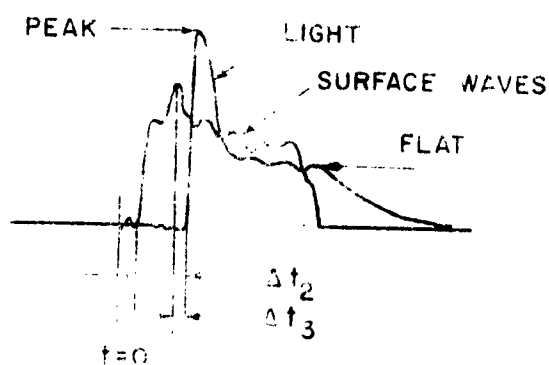
The experimental data plotted in Figure 3 indicate the presence of a standing wave type of fluctuation superimposed on the surface wave and light intensity. Their magnitude remains small however and comparable to the self perturbations introduced by the moving probe. We tentatively conclude therefore

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\* The sharp decrease at  $x' = 250$  mm is partly due to the increased cross section of the tube there.



(a)



(b)

Figure 2. a) Detected RF surface waves and light intensity (along the tube, with plasma) as a function of time, with distance  $x'$  between probe or quartz fibers and waveguide as parameter. Neon 17.5 mm Hg, magnetron power = 25 kw peak,  $p = 30$  mm,  $0.5 \mu\text{s/cm}$ : b) Explanatory sketch for part (a) for the definition of  $\Delta t_2$ ,  $\Delta t_3$ , peak and flat.

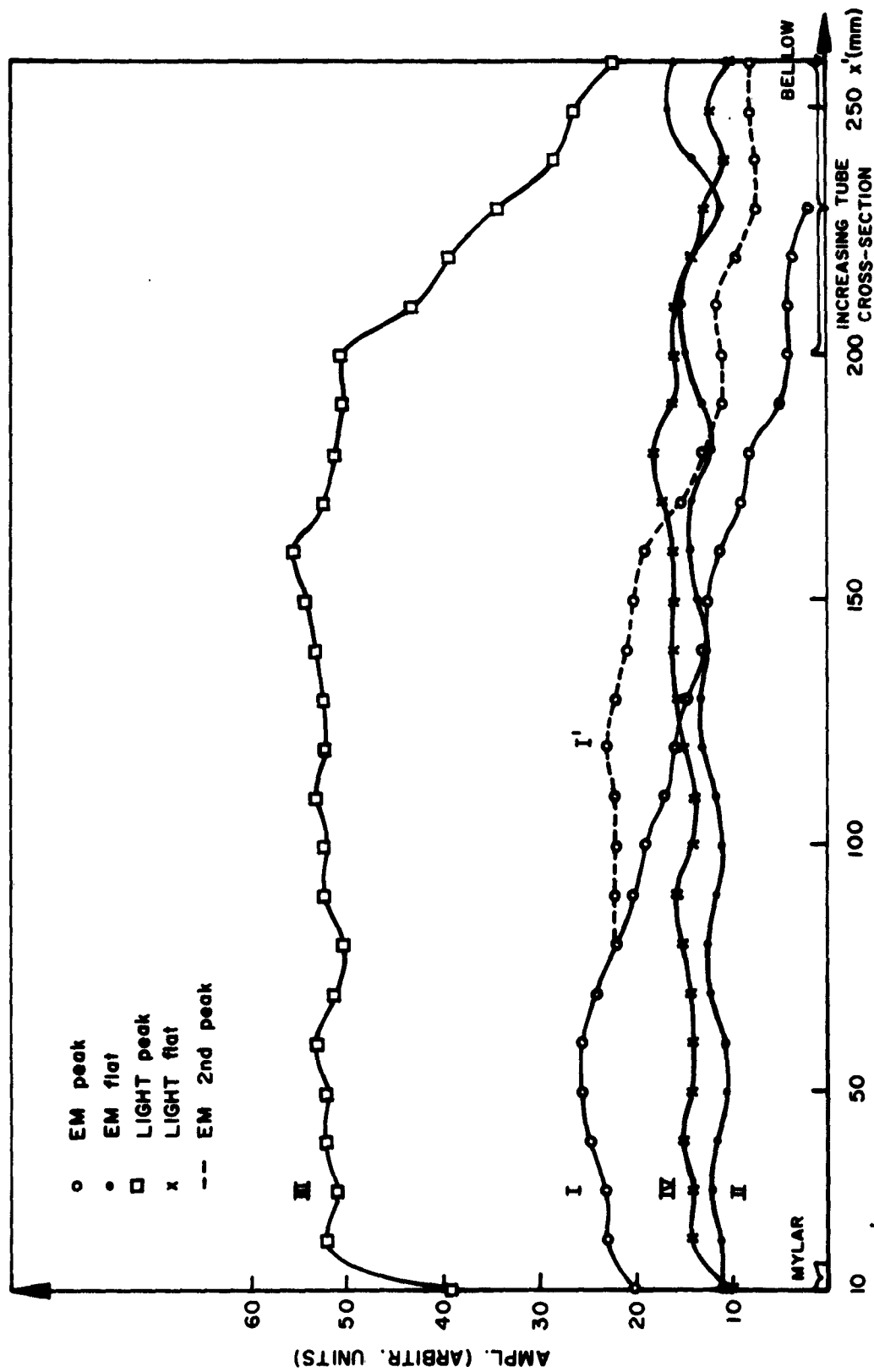


Figure 3. Amplitude variation (arbitrary units) of the RF surface waves and light intensity detected along the tube as a function of the distance  $x'$  from the waveguide. Curves I, I' and II correspond respectively to the first peak, second peak and flat of the RF surface waves; curves III and IV respectively to the peak and flat of the light.

Neon 17.5 mm Hg, magnetron power = 25 kw peak,  $p = 30$  mm.

that, if a standing wave exists along the tube, it is sufficiently small to be neglected and will certainly not greatly interfere with the propagation or be at the origin of the previously observed sound wave discontinuities.

The detection within the duration of the magnetron pulse of a RF field along and outside the tube and the alteration of its shape with the distance from the waveguide are compatible with a surface mode of propagation. Further support is given to the existence of such a mode by the various time delays observed in Figures 1 and 2. The RF field is not detected by the probe before the transmitted magnetron pulse gets attenuated by the breakdown of the plasma inside the waveguide, as indicated by the constancy of  $\Delta t_1$ , and the light is not detected before the RF field has reached its maximum, as indicated by the constancy of  $\Delta t_3$ ; these two observations point out the mutual dependence of the RF field and the plasma on each other. In addition, the time at which the RF field maximum and the light are detected increases with the distance from the waveguide, as indicated by the increasing risetime and  $\Delta t_2$ ; this means that the progression of the surface wave and the plasma is fast but finite. The average velocity of this progression can be calculated from the change in  $\Delta t_2$  over a known distance

$$\langle v \rangle = \frac{dx'}{d(\Delta t_2)}$$

Using the data obtained from Figure 2 and from measurements not reported here, we get:

$$x' = 20 \text{ to } x' = 130 \text{ mm} \quad \langle v \rangle = \frac{11 \text{ cm}}{0.16 \mu \text{ s}} = 69 \text{ cm}/\mu \text{ s}$$

$$x' = 130 \text{ to } x' = 250 \text{ mm} \quad \langle v \rangle = \frac{12}{0.47} = 25.5 \text{ cm}/\mu \text{ s}$$

$$x' = 210 \text{ to } x' = 250 \text{ mm} \quad \langle v \rangle = \frac{4}{0.27} = 15 \text{ cm}/\mu \text{ s}$$

The electron thermal velocity at  $\sim 12000^\circ \text{ K}$  (typical value for a sustained discharge in Neon) and room temperature is respectively 75 and 12  $\text{cm}/\mu \text{ s}$  where for the calculation, the following relation has been used:

$$\langle v \rangle = \sqrt{3 k T_e / m}$$

Thus the progression velocity of the plasma is comparable to the thermal velocity of the electrons at a temperature close to and below  $12000^{\circ}$  K. This progression is faster near the waveguide than at the end of the plasma column. These characteristics were also expected for a surface mode of propagation. When the calculations are applied to the Helium plasma, a progression velocity exactly twice as fast is obtained; it should be remembered that the thermal velocity of the electrons in a Helium plasma is also higher. We believe therefore that the RF field detected up to great distances along the tube is the result of a surface mode of propagation; as already mentioned before, we believe also that the surface waves, by their radial field distribution, are at the origin of the otherwise unexplainable cylindrical sound waves observed in the tube up to large distances from the waveguide. Another effect attributed to the surface waves is described in Section 4 of this report.

### 3. Mixture of Gases

#### 3.1 Ionic Sound Waves

We would like to determine what is the type of the waves which are observed to propagate in the plasma afterglow with a velocity above or equal to the sound wave velocity: hydrodynamic or ionic sound wave? Under certain circumstances, these two waves can propagate with nearly the same velocity. In Quarterly Report 9, where we already raised this question, we based our argumentation on the fact that the masses  $M$  and  $M_1$  of the neutral atom and the ion are practically equal, so that the propagation velocity of both waves, given by

$$s = \sqrt{\frac{\gamma k T_g}{M}} \quad (2a)$$

$$s_1 = \sqrt{\frac{\gamma k T_e}{M_1}} \quad (2b)$$

is equal, under the assumption that the gas temperature  $T_g$  and electron temperature  $T_e$  are the same.  $\gamma$  is the ratio of the specific heats and  $k$  is the Boltzmann's constant.

Another argumentation, which seems to apply more closely to our experiment, leads however to the same equality. It is known<sup>1</sup> that in a pure Helium, Neon,

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1. S. C. Brown, Basic Data of Plasma Physics, Wiley and Sons, p. 196.

or Argon discharge, for instance, diatomic (or molecular) ions are continuously formed by triple collisions according to the following reaction:



The mass of this diatomic ion is twice the mass of the monoatomic ion. On the other hand, the ratio of the specific heats, which might be rewritten<sup>2</sup> as:

$$\gamma = \frac{m + 2}{m} \quad (4)$$

where  $m$  is the number of degrees of freedom, may take the value of 3 (instead of the usual 5/3) in the case of a one-dimensional compression ( $m = 1$ ), when almost no randomization of the velocity by collisions occurs. Then, in Equation (2b), the factor 2 from the mass is almost canceled by the factor 1.8 from  $\gamma$ , and the two propagation velocities are again of the same magnitude. The weak points of this derivation are that we probably have some randomization of the velocity at gas pressures around 4 mm Hg, i.e.,  $m$  in Equation (4) takes the value of 3 (or more in the case of a diatomic molecule with one or two rotational degrees of freedom) and that the presence of the diatomic ions themselves is questionable during the time intervals involved in our observations, because the time constant associated with the formation of a diatomic ion, for instance in Helium at room temperature, is given by<sup>3</sup>

$$\tau_{\text{form.}} = \frac{1}{v_{\text{form.}}} = \frac{1}{65 p^2} \quad (5)$$

where  $p$  is the gas pressure in mm Hg. For a 4 mm Hg pressure,  $\tau_{\text{form.}} \approx 1$  ms, which is about five times as long as the maximum time at which the discontinuities can presently be detected by means of the light.

No matter which argumentation is valid, in the assumption that the observed discontinuities are ionic sound waves, then the method described in Quarterly Report 9 and based on the charge exchange in a gas mixture, must bring a change

2. L. Spitzer, Physics of the Fully Ionized Gases, Interscience Publ., p. 13.

3. A. V. Phelps and S. C. Brown, "Positive Ions in the Afterglow of a Low Pressure Helium Discharge," Phys. Rev., 86, 102 (1952).

in the propagation velocity of the discontinuities, as soon as the ions of the majority gas have exchanged their charge with the atoms of the minority gas. Therefore, the new propagation velocity must be that of the ionic sound wave in the impurity gas, where  $M_1$  is the monoatomic ion mass of the impurity and  $\gamma$  is probably equal to 3, due to long range interaction by Coulomb forces between ions.

### 3.2 High Percentage Mixtures

In case the percentage of the impurity gas is increased to an unusually high value, say ten percent, then the discharge will occur mainly in that gas, due to its lower ionization potential. Assuming now, that an ionic sound wave is excited, its propagation will obviously take place at a velocity associated with the ion mass of the impurity gas; the majority gas has no effect. On the other hand, if a hydrodynamic sound wave is excited, its propagation will take place at a velocity associated no more with the atom mass of the majority gas only, but with the effective mass of the mixture; here, the large percentage of a much heavier gas has an effect. This effective mass is the sum of the masses of the components, A and B, weighted by their partial pressures:

$$M_{\text{eff}} = M_A \frac{p_A}{p_{\text{tot}}} + M_B \frac{p_B}{p_{\text{tot}}} \quad (6)$$

with  $p_{\text{tot}} = p_A + p_B$ . Table I compares the mass and sound velocity for the majority gas alone to the effective mass and sound velocity for a mixture of gases at one and ten percent with Helium, Neon, and Argon. Actually, we have given in Table I the atomic weight instead of the atom mass, and expressed the velocity in cm/ $\mu$ s. We predict therefore that, for a hydrodynamic sound wave

TABLE I

| Mixture     | M  | $M_{\text{eff}}$ | s     | $s_{\text{eff}}$ |
|-------------|----|------------------|-------|------------------|
| He + 1% Ne  | 4  | 4.16             | 0.100 | 0.0985           |
| He + 10% Ne |    | 5.6              |       | 0.085            |
| He + 1% Ar  | 4  | 4.36             | 0.100 | 0.096            |
| He + 10% Ar |    | 7.6              |       | 0.073            |
| Ne + 1% Ar  | 20 | 20.2             | 0.045 | 0.0449           |
| Ne + 10% Ar |    | 22               |       | 0.043            |

only, the propagation velocity in a high percentage mixture should be substantially lower than in the pure majority gas.

We should mention that ionic sound waves have apparently been observed recently in DC arcs at the Oak-Ridge National Laboratory.<sup>4</sup> Except for the dimensions of the tube (1/4" i.d., 23 cm long), the conditions of the experiment were different from ours. A DC electron beam (< 1 amp), confined by a longitudinal magnetic field, was fired along the axis of the tube, the ends of which were closed by grounded metallic plates. The pressure was extremely low ( $10^{-3}$  mm Hg). They detected the fundamental and harmonic frequencies built up in this sort of cavity by waves oscillating between the two end plates. The corresponding propagation velocities fit the theory (our Equation (2b)), when  $M_1$  was the monoatomic ion mass,  $\gamma = 3$  and  $T_e$  was taken as the average excitation potential 17 ev. (130,000°K!) At higher pressures (1 mm Hg), the frequency of these oscillations were much lower and supposed to be due to usual hydrodynamic sound waves.

### 3.3 Experimental Results and Discussion

As mentioned in Quarterly Report 9, more experimental data on discontinuity propagation in mixture of gases should be collected before any conclusion on the existence of ionic sound waves in our plasma can be reached. We have observed then\* that the propagation of the discontinuities, in some cases, suffered a sudden change in velocity, which brought them below the sound velocity in the majority gas at room temperature. We first decided to duplicate these experiments to verify that the observed variations in the velocity were not accidental or due to uncontrolled experimental parameters.

Although not identical, similar results have been obtained for the mixture of 4.1 mm Hg He with 0.4, 2 or 40% Ar (respectively 0.01, 0.05 and 1 percent), as well as 16.5 mm Hg Ne with 1.5% Ar (0.01 percent). They are plotted in Figure 4 on a v-t diagram, similar to Figure 7 in Quarterly Report 9. The solid and dashed lines correspond respectively to the first and second discontinuity; the points on the curves are symbols and not actual measurement data; the arrows indicate the sound velocity in He, Ne and Ar at room temperature; the conditions

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4. I. Alexeff and R. V. Neldigh, "Observation of Ionic Sound Waves in Plasmas," *Phys. Rev. Letters*, 223 (September 15, 1961).

\* Quarterly Report 9, Figure 7.

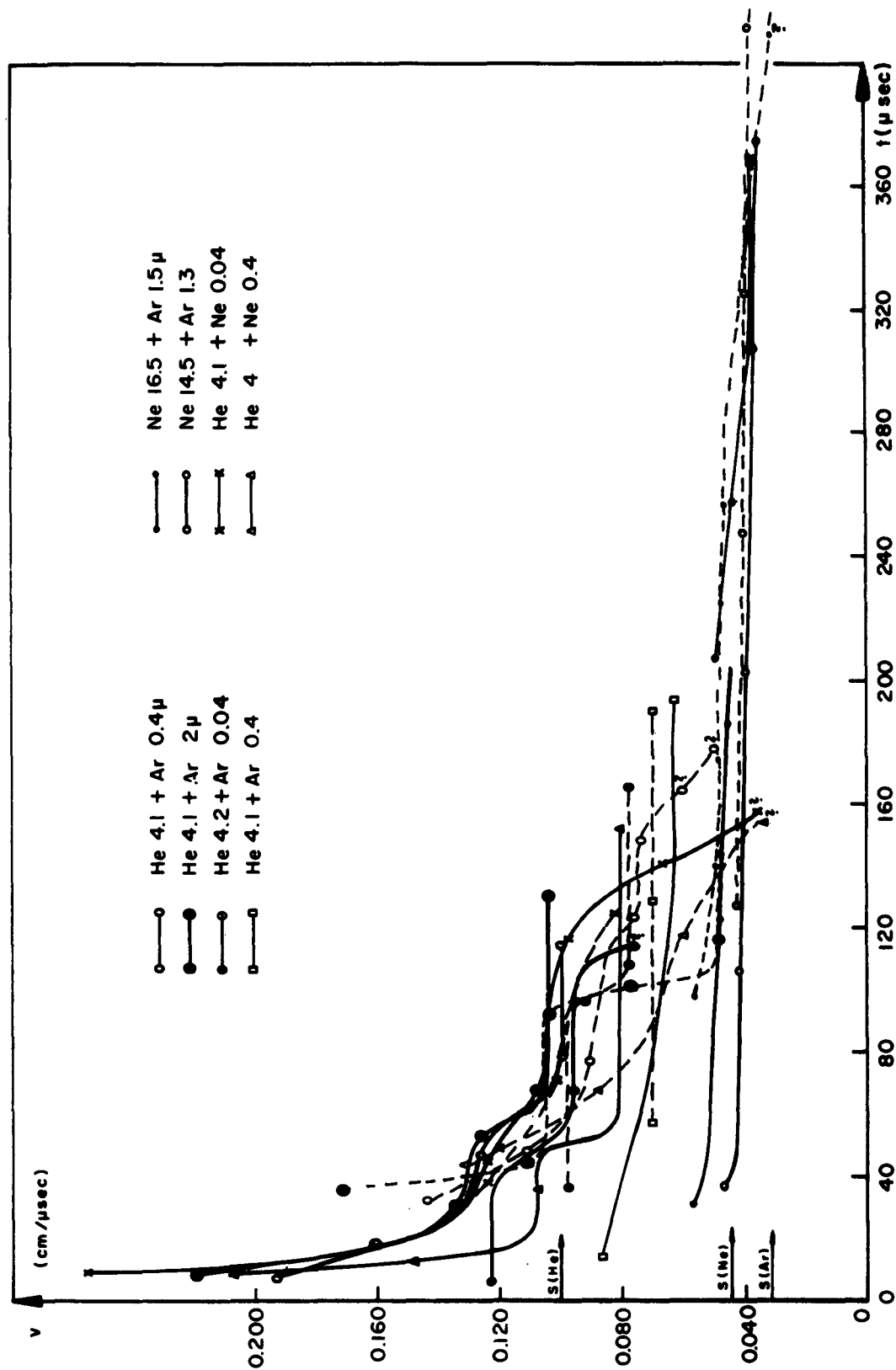


Figure 4. Velocity variation of the first (solid line) and second (dashed line) discontinuities vs time, as computed from their propagation in the decay of the afterglow in mixtures of Helium with Neon or Argon and Neon with Argon. Power = 300 kw peak, repetition = 250 to 1000 cps, penetration  $p = 30$  mm. Symbols are not data points, but identify the curves according to key.  $S( )$  = sound velocity in the majority gas at room temperature.

of the experiment were as usual: 300 kw peak RF power, 14  $\mu$ s pulse duration, 250 to 1000 cps repetition frequency, tube penetration into waveguide  $p = 30$  mm, cylindrical tube 5.5 mm i.d., and light observation by means of 4 quartz fibers in a bunch. It is seen on this figure that the second discontinuity in the mixtures indicated above, decreases well below the sound velocity in Helium or Neon, whereas the first discontinuity does not depart too much from this value. A new measurement in 4.1 mm Hg He with 0.04 mm Hg Ne (1 percent) shows a similar tendency, although the first discontinuity now reaches a lower velocity than the second one. Consequently, the measurements reported previously and verified here were not accidental and effectively exhibit a character different from that of a pure sound wave.

The interpretation of the present and previous\* results is difficult in view of the measurement errors and the lack of close similitude in the velocity variations of the discontinuities. On a more or less statistical basis, the following observations can be made, although single events may contradict them:\*\*

1. The general time variation of the velocity for any one percentage of any one gas mixture is reproducible.
2. The lowest propagation velocities are generally observed with low percentage mixtures.
3. Eighteen observations show a propagation velocity below that of a sound wave in the majority gas. We may therefore suspect them to correspond to an ionic sound wave in the impurity gas, in which either mono- or possibly diatomic ions are present and are subjected either to a one-dimensional compression ( $\gamma = 3$ ), or possibly to a randomization ( $\gamma = 5/3$ ). The number of observations in each type of mixture, for which the lowest observed propagation velocities "satisfy" or "not satisfy" Equation (2b) (theoretical velocity at room temperature) for each of the possibilities mentioned above, is given in the upper part of Table II. They can be compared to the number of observations for which the lowest velocity corresponds to a hydrodynamic sound wave in the majority gas (Equation (2a)).

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\* Figure 7 in Quarterly Report 9.

\*\* These observations apply to the smallest velocity detected during each experiment and assume that room temperature prevails at that time. The first three observations do not apply to the 10 percent and to some of the 1 percent admixture experiments, for which another explanation is given later.

TABLE II

| Type of Wave                          | $\gamma$ | Satisfy Eq. (2b) |         |         |     | Do Not Satisfy Eq. (2b) |         |         |     |
|---------------------------------------|----------|------------------|---------|---------|-----|-------------------------|---------|---------|-----|
|                                       |          | He + Ne          | He + Ar | Ne + Ar | tot | He + Ne                 | He + Ar | Ne + Ar | tot |
| ionic<br>monoatomic                   | 5/3      | 0                | 1       | 2       | 3   | 3                       | 10      | 2       | 15  |
|                                       | 3        | 0                | 3       | 0       | 3   | 3                       | 8       | 4       | 15  |
| ionic<br>diatomic                     | 5/3      | 1                | 0       | 0       | 1   | 2                       | 11      | 4       | 17  |
|                                       | 3        | 0                | 1       | 1       | 2   | 3                       | 10      | 3       | 16  |
| hydrodynamic<br>sound (Eq. 2a)        | 5/3      | 1                | 5       | 2       | 8   |                         |         |         | 18  |
| ionic<br>monoatomic<br>(majority gas) | 3        | 2                | 4       | 2       | 8   | 1                       | 5       | 2       | 8   |

4. In the course of its rapid variation in the early afterglow, the velocity of six discontinuities shows the expected but perhaps accidental particularity of remaining almost constant between about 30 and 50  $\mu$ s. The relatively high value of the velocity (higher than sound velocity) at which this phenomenon occurs does, however, correspond to the velocity of an ionic pseudo sound wave, with  $\gamma$  set equal to 3, in the ions of the majority gas, i.e., before a charge exchange occurs. The number of experiments, for which the observed velocities "satisfy" and "not satisfy" Equation (2b), is also given in the lower part of Table II.

The number of observations on ionic propagation which do not correspond to one of the waves listed in Table II is seen to be much greater than that which do fit the theory. Should any ionic sound wave exist, there is a slightly greater probability to detect it in the mixture as propagating in the monoatomic ions of the impurity gas with  $\gamma$  equal either to 5/3 or 3. There are, however, many more observations showing a propagation at the usual hydrodynamic sound wave velocity, with  $\gamma = 5/3$ . Statistically, the same number of observations exhibits, during a short time in the early afterglow, the propagation of an ionic pseudo sound wave in the majority gas, with  $\gamma$  equal to 3.

Better and more coherent results have been obtained from the high percentage mixtures (1 percent and 10 percent), for which the velocity of propagation in the majority gas is slowed down by the large amount of heavier gas mixed with it. The experimental data closely corresponds to the calculated velocities we have derived from the concept of an effective mass and which are given in Table I. The fact that the change in velocity follows Equation (2a) (where  $M = M_{\text{eff}}$ ) and not Equation (2b) (where  $M = M_1$ ), is an indication that, at least in a 1 to 10 percent mixture, the propagation is characteristic of a hydrodynamic sound wave.

#### 4. Microwave Detection

##### 4.1 Conditions of the Experiment and Choice of the Frequency

The detection of the discontinuities by means of a microwave signal was started in order to prove that the method of detection based on the light intensity was valid. The microwave approach makes use of the interaction of a plasma with a weak RF signal. Since this experiment is intended to duplicate some of the

light measurements, the microwave and light detection must obviously take place at the same location, i.e., at the same cross section along the part of the tube which is outside the S-band waveguide.\* The interaction occurs therefore between the plasma available in the tube during the afterglow following the magnetron pulse (or the breakdown produced by the surface waves) and a separate low level X-band microwave. The X-band microwave source should be independent of the magnetron since the discontinuity has to be detected long after the termination of the magnetron pulse.

The choice of the microwave frequency to be used for this detection proceeds from the consideration of two opposite effects. On the one hand, the interaction of a wave with a plasma (both for the attenuation of the wave or the excitation of the plasma) will usually take place with great efficiency when the ratio  $\omega_p/\omega$  is not too far from unity ( $\omega$  = wave frequency,  $\omega_p$  = electron plasma frequency). Therefore, the attenuation of the (low level) microwave, used for the detection, by the plasma excited by the magnetron pulse will be usually more important if its frequency is not too far from that of the magnetron ( $p \approx 3000$  mc, 10 cm wavelength).\*\* On the other hand, the length of the plasma column over which this interaction occurs should be comparable to or smaller than the finite thickness of the discontinuities (estimated to about 1 cm). This problem of spatial resolution requires that the system guiding the microwave be of small dimensions (i.e., suitable for small wavelengths). A convenient compromise is achieved by using a flat section of an X-band waveguide, in which a hole has been drilled in the middle of the large walls for the passage of the glass tube. The thickness of the waveguide (4 mm) satisfies the condition for space resolution and its width (33 mm) minimizes the disturbing effects of the hole (9 mm i.d.). We rely on the high power of the magnetron to produce a plasma of high enough density to attenuate, in this geometry, the propagation of an X-band frequency (7600 to 11000 mc signal); this is the case if  $\omega_p/\omega_{\text{magn.}} \approx 3$ . As low frequency signals enable

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\* In this section we deal with two different microwave frequencies and with their corresponding waveguide. The high power microwave pulse from the magnetron ( $\sim 3000$  mc), which produces the breakdown of the gas, propagates in an S-band waveguide, whereas the microwave frequency used for the detection (7600 to 11000 mc) propagates in an X-band waveguide.

\*\* Under such circumstances, however, high power may be coupled from the magnetron into the detection system and destroy the crystal detector.

the detection of low electron densities, the lower the X-band frequency, the longer in the afterglow the decaying electron density will produce attenuation of the X-band microwaves. We expect therefore that a detection with a microwave signal at 7600 mc should prove more sensitive than at 11000 mc.

The discontinuities are believed to be sound like waves. As such, their propagation is characterized by a local compression of the medium, moving along the tube at the corresponding sound velocity. During this compression, the density of all constituents of the medium is slightly increased. This phenomenon was considered to be at the origin of the small increase in the light output of the afterglow (enhanced recombination) on which we based our measurements. If true, the same increase in the electron density should produce an enhanced attenuation in the transmission of the X-band microwaves.

#### 4.2 Surface Mode Resonance

It is an experimental fact, that in a plasma post experiment, the range of detection by means of microwaves is limited towards the high density (high attenuation, early afterglow) by large variations in the amplitude of the transmitted signal.\* In the course of the plasma decay (increasing microwave transmission corresponding to decreasing electron density), the amplitude and the spacing of these fluctuations become smaller. The same change is observed when the microwave frequency is increased. Leiby and Goldan\*\* have given an explanation to this phenomenon, based on a resonance oscillation of surface waves, excited at the surface of the plasma post, in the sort of cavity formed by the post section bounded by the two walls of the waveguide. When the wavelength of the surface mode is a multiple of the wall spacing, energy can be coupled to and lost in the plasma outside the waveguide, with the effect of an apparent reduction of the transmission in the waveguide. The wavelength of the surface mode varies from 0 to free space wavelength when the dielectric constant decreases from  $-1$  to  $-\infty$ , or, in view of Equation (1), when the electron density increases from some small value to infinity.\*\*\* Therefore,

\* These variations can be seen in Figures 6 to 8.

\*\* Already mentioned in Section 2.

\*\*\* This is a simplified result of the calculations made by Leiby and Goldan.

in the course of the decay of the electron density in the afterglow, the wavelength of the surface waves decreases and satisfies an increasingly large number of resonance conditions, for each one of them a small "dip" in the microwave transmission is observed, until a sufficiently low electron density is reached, for which the dielectric constant is equal or larger than -1 and the existence of surface modes is no more possible. The effect of a change in the microwave frequency is in first approximation, according to Equation (1), to shift the above mentioned phenomena to a higher or lower electron density, i.e., to make it appear sooner or later in the afterglow. From these considerations, we may expect that the transmission of a microwave signal, at a frequency in the upper part of the X-band spectrum, will be free of fluctuation over a wider range of change in the electron density and, in particular, will permit the detection of our (sound like) discontinuities sooner in the afterglow. At such a high frequency, the full transmission of the microwave signal will evidently occur at a higher electron density, i.e., sooner also in the afterglow. In certain circumstances, however, the choice of a high frequency may prove advantageous.

#### 4.3 Experimental Results

This preliminary experiment was intended to verify the validity of the light detection method. The simple set up shown in Figure 5 was sufficient for that purpose. It consists in a Hewlett-Packard 620 A Signal Generator giving between 7000 and 11000 mc a CW or externally pulsed output of 1 mw, a coaxial to waveguide adapter, a Uniline, two tapered waveguide connecting the flat section to the usual X-band size waveguides and a crystal detector. The tube crosses the setup through the holes drilled in the flat section. A set of quartz fibers detects the light in the tube right at its entrance in or its exit from the X-band waveguide. A long pulsed microwave, triggered at the same time as the magnetron and the scope, is sent into the X-band waveguide, interacts with the plasma built up in the tube by the (S-band) magnetron pulse, is detected by the crystal and displayed on the scope by one of the alternate traces. The other trace records the light picked up in the tube by the quartz fibers. These traces present respectively the characteristic curve of a transmitted microwave signal attenuated by a decaying plasma (almost full attenuation to full transmission, plus the fluctuations due to

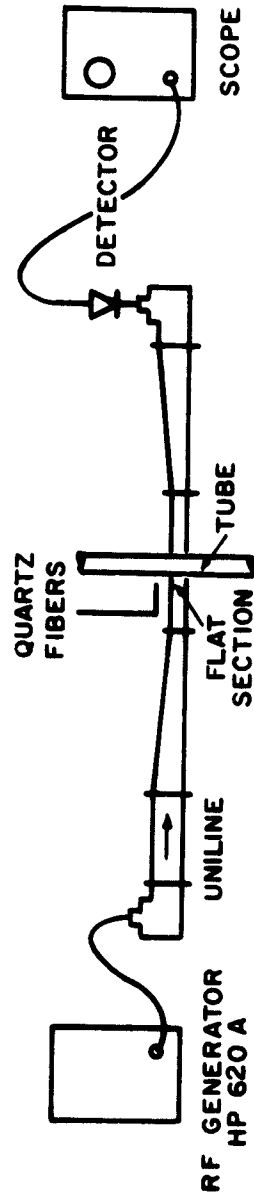


Figure 5. Experimental setup for the detection of the discontinuities by means of X-band microwaves.

surface mode resonance, plus the pulse-off baseline) and the curve of the light output from a decaying afterglow. The distance between the X-band and S-band waveguides is arbitrarily chosen, so that the time at which the discontinuity passes through the X-band waveguide falls within the time interval determined on the transmitted X-band microwave signal by the surface mode resonances and the full transmission. Three gases, Helium, Neon and Argon, at various pressures, have been investigated. Two frequencies have been selected, one in the lower part, the other in the upper part of the X-band frequency spectrum. The (S-band) magnetron power was set to 200 or 250 kw, 250 cps repetition, and the tube penetration into the S-band waveguide was as usual 30 mm. The X-band microwave power was less than 1 mw.

Figure 6 is a picture from the experiment made in Argon 4.1 mm Hg at a frequency of 7880 mc. The X-band waveguide is located at  $x' = 60$  mm and the quartz fibers at  $x' = 65$  mm from the S-band waveguide. The discontinuities are detected on the light at 180 and 280  $\mu$ s, but only the second discontinuity is visible (with some difficulty) on the transmitted X-band signal at 273  $\mu$ s;\* the first discontinuity occurs at a position where the large fluctuations are still present at the beginning of the microwave trace. This is the best observation we could make in Argon. In Neon and Helium, the discontinuities were not detected by the microwaves at that low frequency.

Figures 7, 8 and 9 are pictures taken respectively in Argon 4.1 mm Hg, Neon 16.5 mm Hg and Helium 4.7 mm Hg, but at a frequency of 10700 mc. The quartz fibers are now at the entrance of the tube in the X-band waveguide. In Figure 7, microwave and light detection occurs respectively at 79 and 75 mm, and the first discontinuity at 230  $\mu$ s is easily detected on the microwave trace and at 215  $\mu$ s in the light. The second discontinuity, visible on the light, falls already in the full transmission region of the microwaves. In Figure 8, for the same detection distances, the first discontinuity is also observed on the microwaves at 173  $\mu$ s and on the light at 165  $\mu$ s. As for Argon, the second discontinuity is already in the full transmission region of the microwaves (250  $\mu$ s). In Figure 9, the location of the microwave and light detection

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\* In Figures 6, 7, 8 and 9, the detected discontinuities are pointed out by arrows.

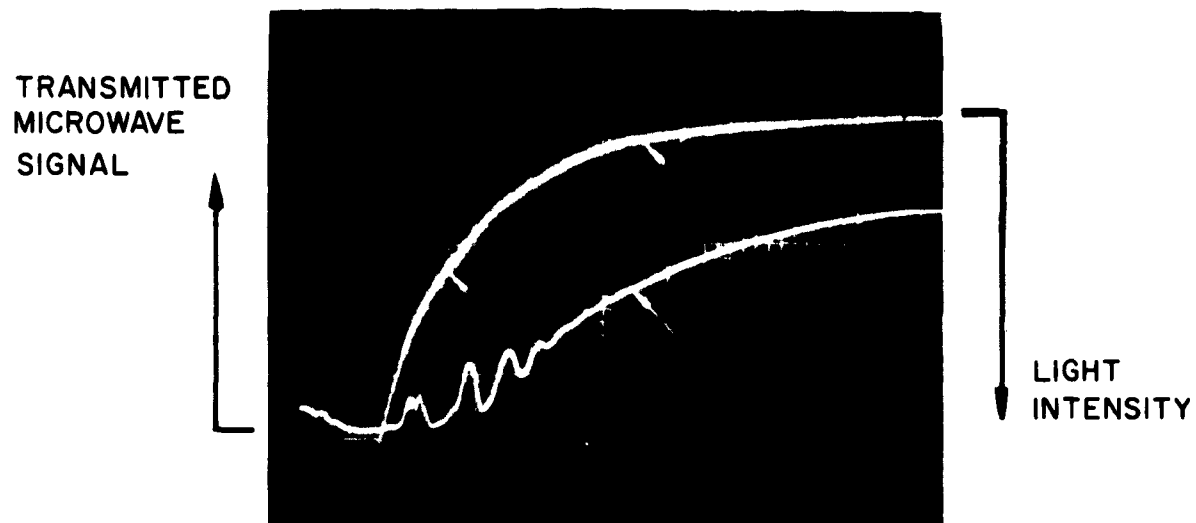


Figure 6. X-band microwave (7880 mc) and light detection of the discontinuities in the decay of a plasma in Argon at 4.1 mm Hg. The detection occurs at  $x' = 60$  mm (microwave) and  $x' = 65$  mm (light). The discontinuities are observed at 273  $\mu$ s (microwave) and 180 and 280  $\mu$ s (light). Magnetron power = 250 kw peak, pulse duration = 1  $\mu$ s, penetration  $p = 30$  mm, 50  $\mu$ s/cm.

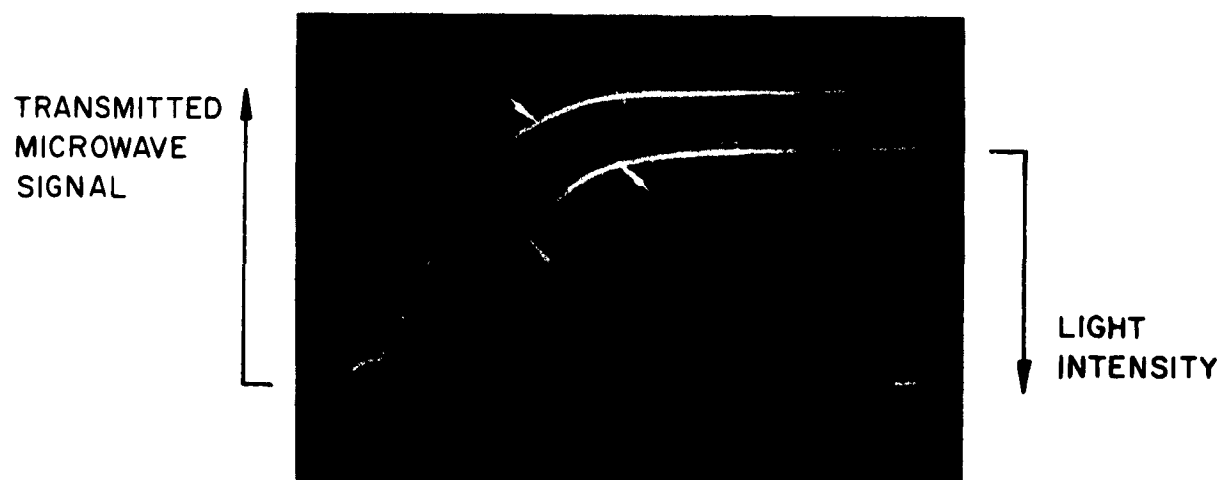


Figure 7. X-band microwave (10700 mc) and light detection of the discontinuities in the decay of a plasma in Argon at 4.1 mm Hg. The detection occurs at  $x' = 75$  mm (light) and  $x' = 79$  mm (microwave). The discontinuities are observed at 230  $\mu$ s (microwave) and 215 and 334  $\mu$ s (light). Magnetron power=200 kw peak, pulse duration = 1  $\mu$ s, penetration  $p = 30$  mm, 50  $\mu$ s/cm.

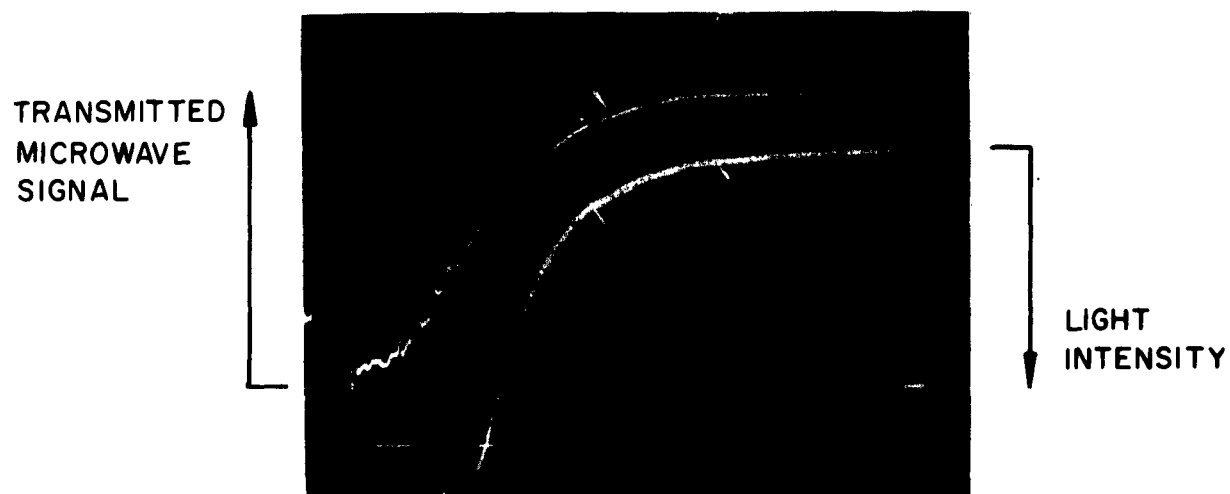


Figure 8. X-band microwave (10700 mc) and light detection of the discontinuities in the decay of a plasma in Neon at 16.5 mm Hg. The detection occurs at  $x' = 75$  mm (light) and  $x' = 79$  mm (microwave). The discontinuities are observed at 173  $\mu$ s (microwave) and 165 and 240  $\mu$ s (light). Magnetron power = 200 kw peak, pulse duration = 1  $\mu$ s, penetration  $p = 30$  mm, 50  $\mu$ s/cm.

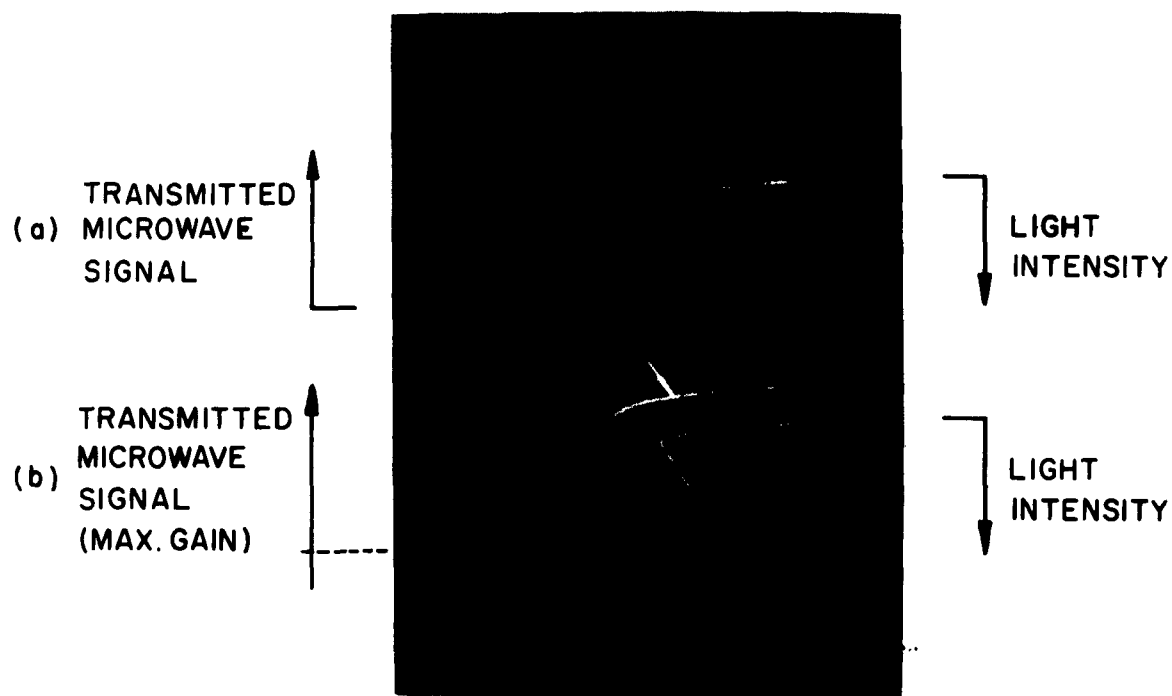


Figure 9. a) X-band microwave (10700 mc) and light detection of the discontinuities in the decay of a plasma in Helium at 4.7 mm Hg. The detection occurs at  $x' = 65$  mm (light) and  $x' = 70$  mm (microwave). The discontinuities are not observed. Magnetron power = 200 kw peak, pulse duration =  $1 \mu\text{s}$ , penetration  $p = 30$  mm,  $10 \mu\text{s/cm}$ : b) Same picture, but maximum gain of the amplifiers. The first discontinuity is observed at  $59 \mu\text{s}$  (microwave) and  $54 \mu\text{s}$  (light).

has been set closer to  $x' = 70$  and 65 mm, since the propagation velocity of the discontinuities is faster. With the same gain as before (Figure 9a) nothing can be detected on the microwave trace; by increasing the available gain to maximum (Figure 9b), the first discontinuity is observed on the light at 54  $\mu$ s and with great difficulty on the microwaves at 59  $\mu$ s.

Our various and preliminary observations on microwave detection may be summarized as follows:

1. Microwave and light detection of the discontinuities are in agreement as far as time of observation and velocity of propagation are concerned. Therefore the observation of the change in the light output of the afterglow is a valid method for the detection of the discontinuities.

2. In the course of this preliminary experiment, the X-band microwave detection of the discontinuities at the two selected frequencies have been done with some difficulty in Argon, with some more in Neon and with great difficulty in Helium.

3. With the two selected frequencies (7880 and 10700 mc), the highest one shows the strongest increase in attenuation when the discontinuities pass through the X-band waveguide.

4. The microwave transmission is almost brought to cut-off. That means that the electron density in the plasma (even 5 to 10  $\mu$ s after the breakdown) is much higher than expected ( $10^{12}$ , perhaps  $10^{13} \text{ cm}^{-3}$ ).

5. At 10700 mc, the recovery to full X-band microwave power takes, as expected, less time than at 7880 mc.

6. At 10700 mc, the large fluctuations in the early part of the transmitted X-band microwave signal are smaller and closer to one another than at 7880 mc. This observation, predicted on the assumption of surface mode resonance in the X-band waveguide, might be an indirect proof of their existence.

#### Future Plans

The microwave system will be modified in order to tentatively measure the change produced in the electron density and the collision frequency of the plasma by the presence of the discontinuity.

Another method should be found in order to determine with more success the hydrodynamic or ionic character of our discontinuities.

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